An Ion-Trap Phonon Laser

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Cooling of atoms and ions [1,2] using a red-detuned laser has had a profound impact on science and technology [3-5]. In this work simultaneous laser cooling and blue-detuned laser pumping of a Mg^+ ion in a Paul trap is studied. Blue-detuned pumping is conventionally referred to as the heating regime, and in early work, remarkably complex behaviors (bistability and limit cycles) have been associated with this regime [6,7]. These behaviors have so far not been fully explained. Here, it is shown that blue-detuned pumping, as opposed to heating, causes stimulated emission of center-of-mass phonons, leading to coherent oscillatory motion of the ion in analogy with a laser. Mechanical amplification is calculated as well as the threshold pumping condition for oscillation. A single ion in a linear radio-frequency trap is studied to verify these predictions (figure 1 left panel). Blue-detuned pumping of the magnesium D2 transition at 279.6 nm provides amplification along the long axis of the ion trap so as to excite only axial oscillations. A slightly off-axis, red-detuned beam cools the center-of-mass motion to approximately 1 mK. The experimental arrangement is identical to that detailed in ref. [8].

Imaging the ion motion was possible by monitoring luminescence caused by the cooling and amplification beams (Figure 1 right panel). With increasing amplification beam intensity there is a transition to a double-lobed pattern, produced by time averaging of the oscillatory motion of the ion. Further increases in intensity lead to larger amplitudes. Measurements of the threshold and the amplitude of motion versus pumping using such plots are in excellent agreement with the theory. The production of semi-classical, vibrational coherence can be a new tool for study of quantum phenomena using ionic systems, or to drive modes within an effective ionic medium.

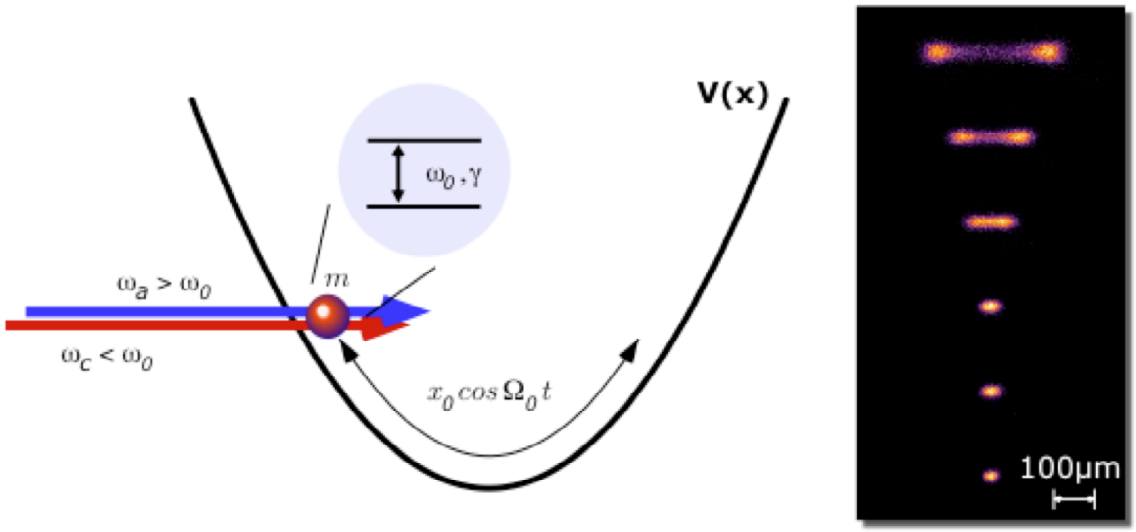

Fig. 1 Left panel: ion in a harmonic trap with secular frequency Ω_o excited with both a cooling beam at frequency ω_c and an amplification beam at frequency ω_a The ion transition (frequency ω_o) has linewidth γ. Right panel: a series of images of ion luminescence in which the amplification beam intensity is increased from lower to upper images. The cooling beam intensity is constant and the lowest image features no amplification. The ion's lateral motion is time averaged, and a threshold is apparent between the third and fourth images.

References

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